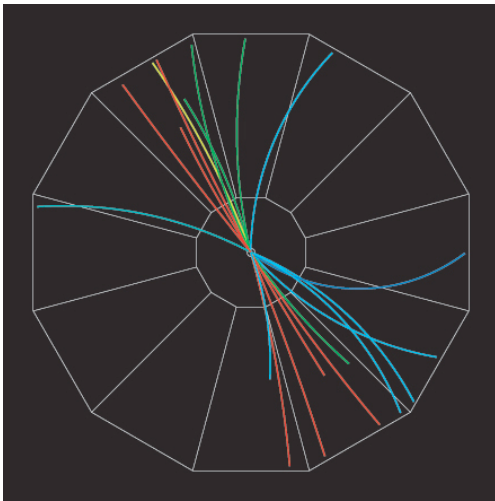


Gluon polarization measurements at STAR

Joanna Kiryluk (MIT)

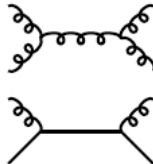
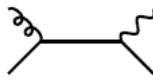
*Workshop on 'Contribution of the Gluon Spin to the Proton Spin'
3 December 2005, RIKEN, Wako, Japan*



Outline:

1. Introduction
2. STAR detector at RHIC
3. Cross section and A_{LL} in inclusive jet production in polarized p+p collisions at $\sqrt{s}=200$ GeV - preliminary results
4. Summary and outlook

Determination of gluon polarization - a major emphasis at STAR-Spin program at RHIC

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \rightarrow \pi + X$	$\vec{g}\vec{g} \rightarrow gg$	Δg	
	$\vec{q}\vec{g} \rightarrow qg$		
$\vec{p}\vec{p} \rightarrow \text{jet(s)} + X$	$\vec{g}\vec{g} \rightarrow gg$	Δg	(as above)
	$\vec{q}\vec{g} \rightarrow qg$		
$\vec{p}\vec{p} \rightarrow \gamma + X$	$\vec{q}\vec{g} \rightarrow \gamma q$	Δg	
$\vec{p}\vec{p} \rightarrow \gamma + \text{jet} + X$	$\vec{q}\vec{g} \rightarrow \gamma q$	Δg	
$\sqrt{s} = 200(500) \text{ GeV}$			
Known NLO corrections (all cases)			

Inclusive production

High production rate

Classic 'tool' to access gluon distribution function - but rare probes

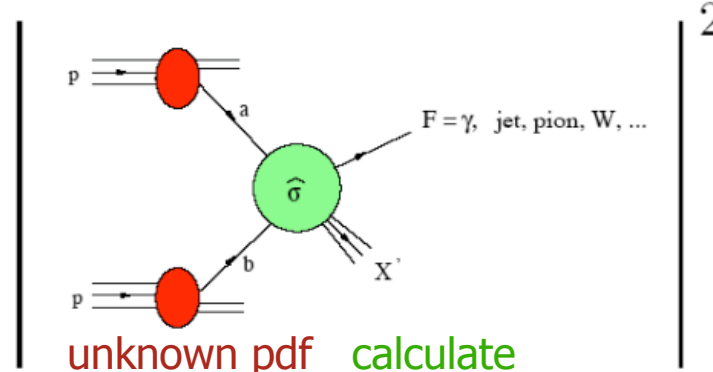
How are we going to access information about pol. gluon distribution function?

Inclusive particle/jet production in pp interactions (1)

- Cross section for inclusive (single) particle production

$$p_T^3 \frac{d\sigma}{dp_T d\eta} =$$

measure



$$+ \mathcal{O}\left(\frac{\lambda}{p_T}\right)^n$$

$\sigma \propto \text{pdf} \otimes \text{pdf} \otimes \text{hard scattering} \otimes (\text{fragmentation})$

$$p_T^3 \frac{d(\Delta)\sigma^{pp \rightarrow FX}}{dp_T d\eta} = \sum_{abc} \int_{x_a^{\min}}^1 dx_a \int_{x_b^{\min}}^1 dx_b (\Delta) f_a(x_a, \mu) (\Delta) f_b(x_b, \mu) \\ \times p_T^3 \frac{d(\Delta)\hat{\sigma}^{ab \rightarrow FX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^F, \mu) + P.C.$$

$$x_a^{\min} = x_T e^{\eta} / (2 - x_T e^{-\eta})$$

$$x_b^{\min} = x_a x_T e^{-\eta} / (2x_a - x_T e^{\eta})$$

$$x_T = 2p_T / \sqrt{s}$$

↑ $\hat{\sigma}^{(0)} + \alpha_s \hat{\sigma}^{(1)} + \dots$ perturbative series

for jets - no fragmentation functions are needed (systematics!)

- Asymmetries

$$\sigma = \bar{\sigma} \pm \Delta\sigma$$

$$A_{LL} = \frac{\Delta\sigma}{\bar{\sigma}} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

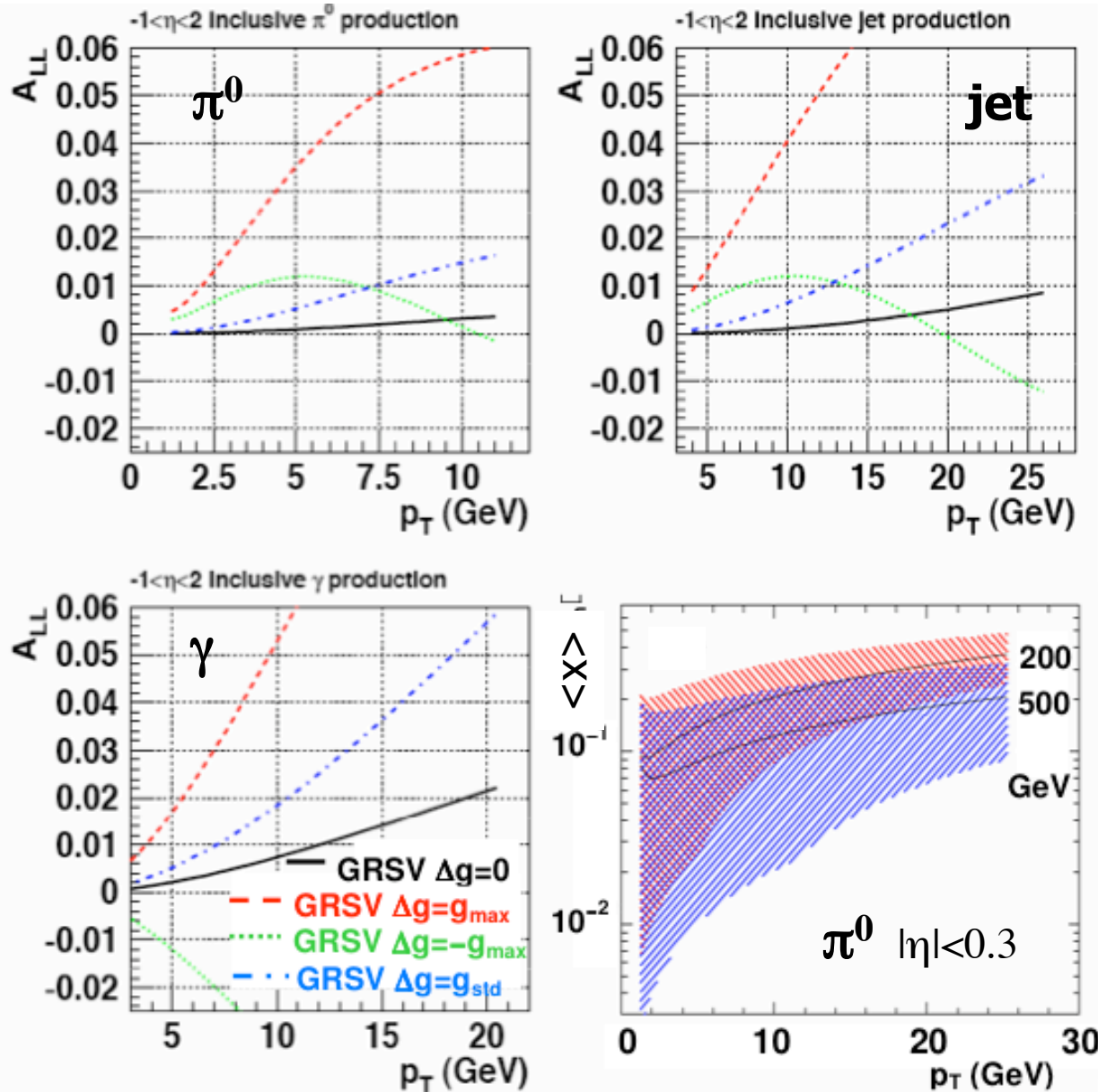
$\Delta\sigma$ - very small (difficult to measure)

We measure asymmetries instead, where most of systematic effects cancel out

Required knowledge of unpolarized pdf's in the measured kinematic region

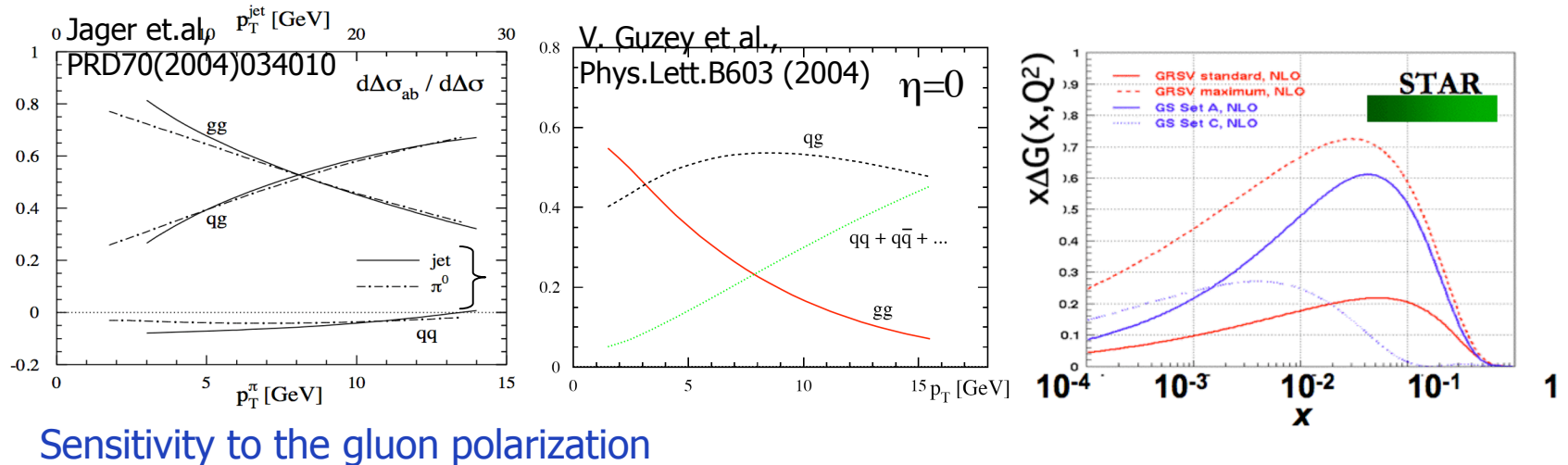
Predictions for A_{LL} in inclusive π^0 , jet and γ production at $-1 < \eta < 2$ (STAR EMC) in pp interactions at $\sqrt{s} = 200$ GeV

From: B.Jager, M.Stratmann and W.Vogelsang



Broad x-range
contributes to each p_T
bin for inclusive yields
 \Rightarrow limited sensitivity to
 $\Delta g(x)$ shape

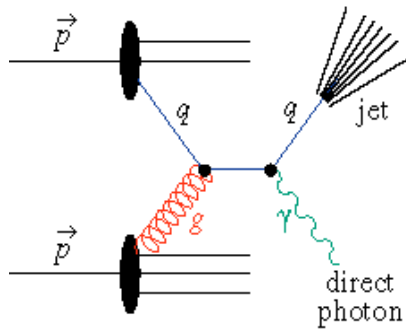
Inclusive particle/jet production in pp interactions (2)



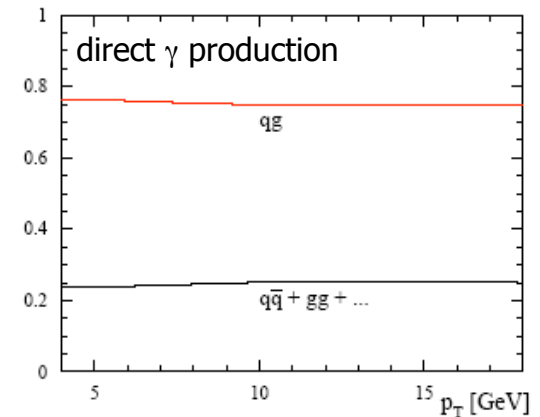
- Convolutions “pdf \times pdf \times cross section” relatively complicated and inversion $A_{LL} = \Delta\sigma / \bar{\sigma} \rightarrow g(x)$ is not straightforward
- At the moment emphasis is on NLO predictions of A_{LL} in terms of “model” Δg , to study the sensitivity of the observable
- Future: CTEQ-style global analysis of variety of A_{LL} data (should include NLO)
- Alternative approach: “correlations” (γ +jet, di-jets, π + π) that probe kinematics in more detail

W.Vogelsang RBRC/BNL, RHIC-AGS User's Mtg talk

Gluon polarization from Prompt Photon Production (1)



Quark-Gluon Compton
scattering dominates ($\sim 75\%$)
direct γ production



The cross section asymmetry A_{LL} for $\vec{p} + \vec{p} \rightarrow \gamma + \text{jet} + X$ (description at Leading Order):

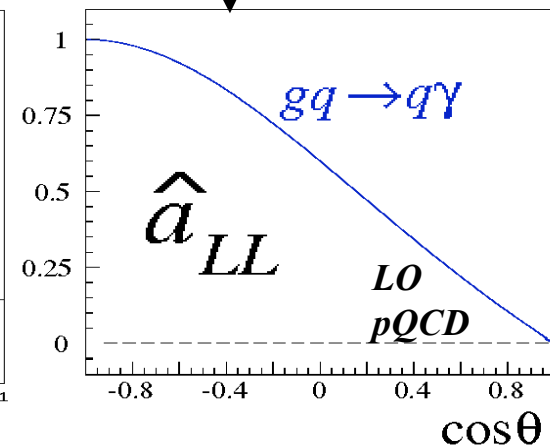
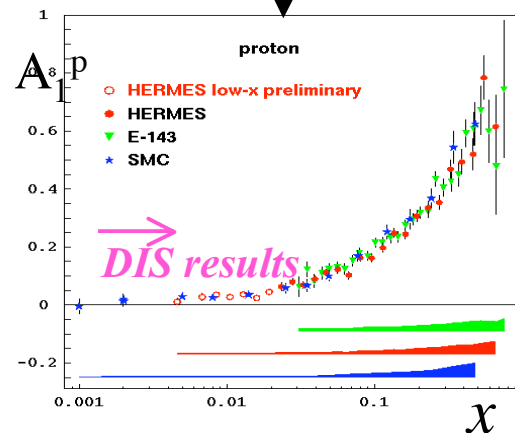
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \approx \underbrace{\frac{\Delta g(x_g)}{g(x_g)}}_{\substack{\text{Direct measurement of gluon polarization} \\ \uparrow}} \times \underbrace{\frac{\sum e_i^2 \Delta q_i(x_q)}{\sum e_i^2 q_i(x_q)}}_{\substack{\text{known from pol. DIS} \\ \downarrow}} \times \underbrace{\hat{a}_{LL}(gq \rightarrow q\gamma)}_{\substack{\text{calculable in pQCD,} \\ \text{scale} \sim p_T^2 \text{ of } \gamma \\ \downarrow}}$$

Parton kinematics reconstruction from p_T^γ , η_γ and η_{jet} measurements:

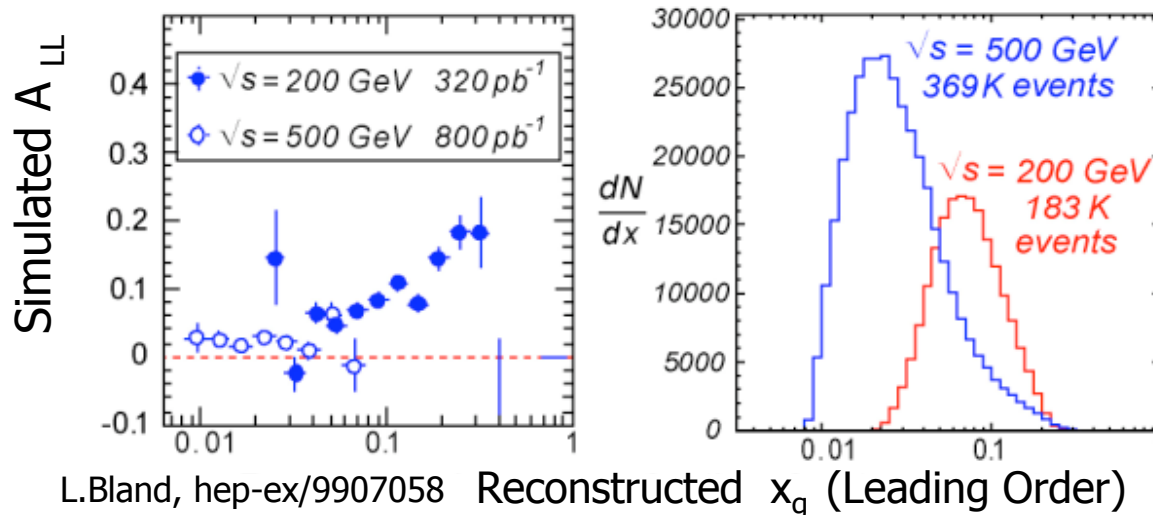
$$x_{1(2)} = \frac{p_T^\gamma}{\sqrt{s}} \left[\exp(\pm \eta_\gamma) + \exp(\pm \eta_{\text{jet}}) \right]$$

where $x_g = \min[x_1, x_2]$

and $x_q = \max[x_1, x_2]$



Gluon polarization from Prompt Photon Production (2)



Two beam energies - large range of x_g - needed to minimize extrapolation errors

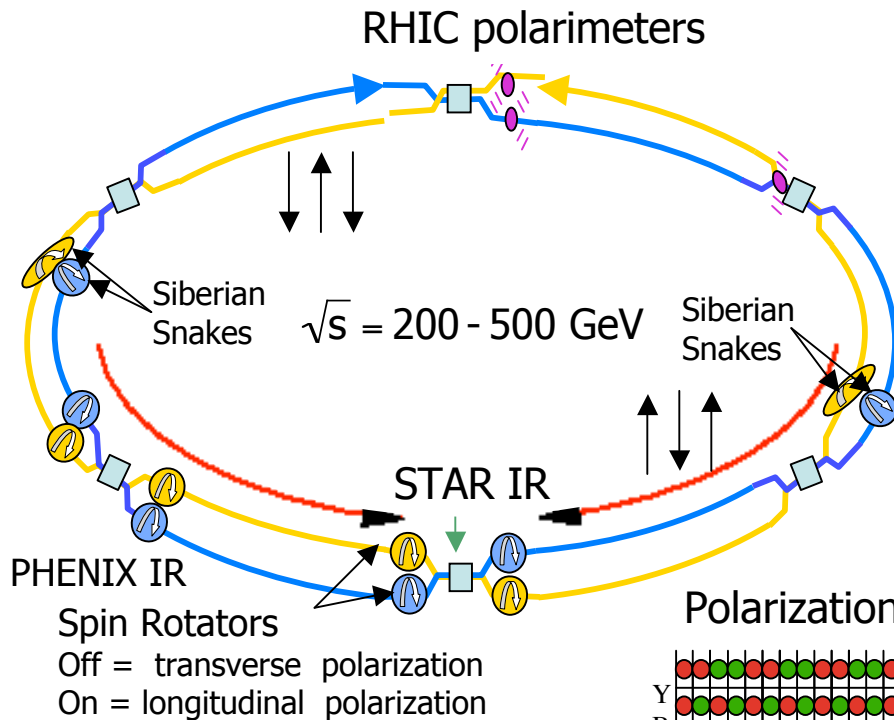
$$\Delta G(Q^2) = \int_0^1 \Delta G(x, Q^2) dx$$

We expect it will be determined to a precision of 0.5

The best determination of ΔG will result from a global analysis of the data from:

- RHIC (STAR, PHENIX) - other channels, e.g. heavy-flavor/di-jet/di-hadron and abundant inclusive jet/pion production (less 'luminosity hungry')
- pDIS (HERMES, COMPASS) - high p_T hadron pair/open charm production (limited x_g kinematic region)
- + possibly(?) eRHIC through $g_1(x, Q^2)$ measurements over a wide kinematic range

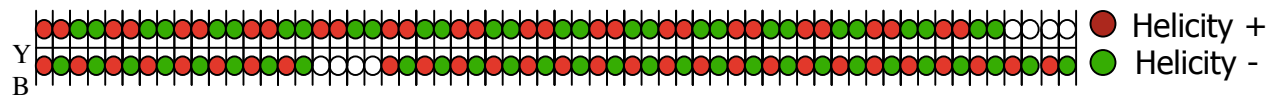
RHIC (*Relativistic Heavy Ion Collider*) - polarized pp collider



- two siberian snakes in each ring:
*stable polarization direction at RHIC - vertical
beam polarization measured by RHIC polarimeters*
- a pair of spin rotators in each ring around STAR
(and PHENIX) IR (Interaction Region):
longitudinal polarization at two Irs

STAR local polarimeter - to monitor beam polarization direction

Polarization pattern at STAR, e.g. in 2004



pp (longitudinal) Run	2003	2004	2005 (on-going analysis)	> 2006 LongTermGoals	
CM Energy	200 GeV			200 GeV	500 GeV
Beam polarization	0.30	0.40	0.45	0.7	0.7
$L_{\text{max}} [10^{30} \text{ s}^{-1} \text{cm}^{-2}]$	6	6	16	80	200
$L_{\text{int}} [\text{pb}^{-1}]$ (STAR,delivered)	0.4	0.4	9	320	800

Preliminary Results

STAR detector

Solenoidal Magnet

- $B = 0.5 \text{ T}$

Tracking Detectors

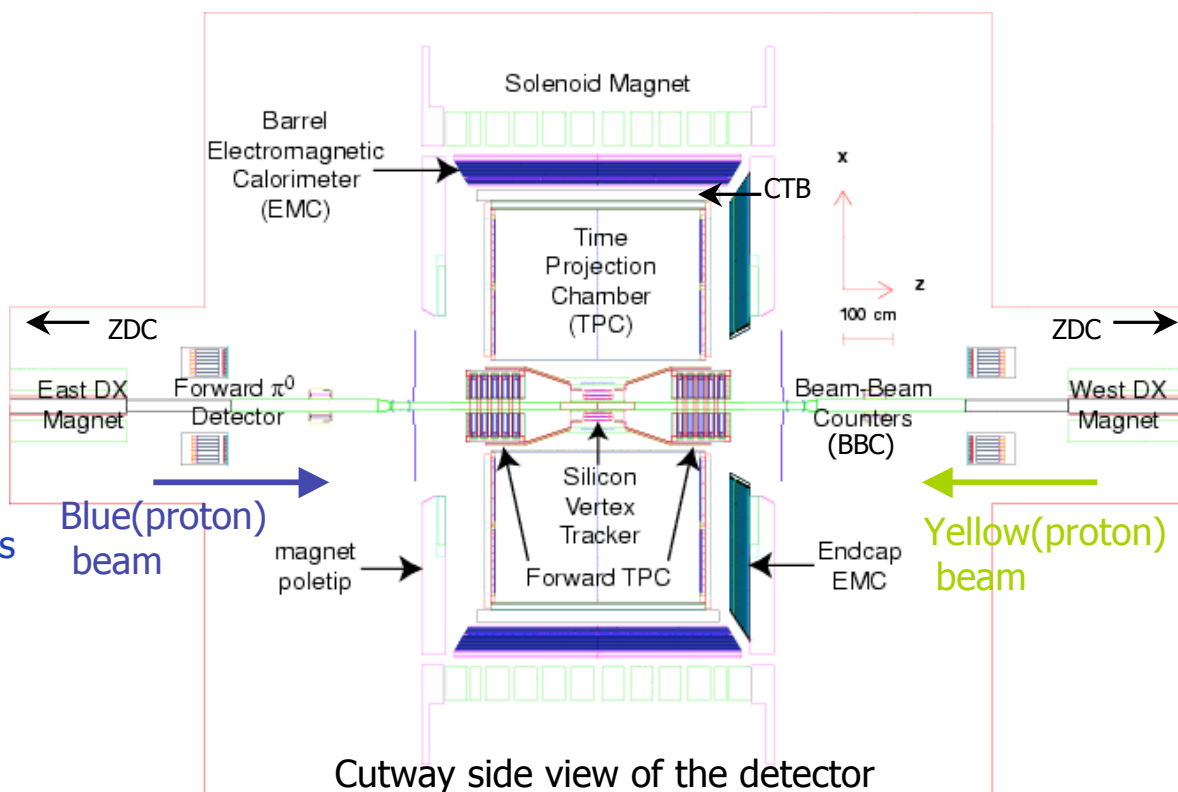
- Time Projection Chamber $|\eta| < 1.6$
- Forward TPC $2.5 < |\eta| < 4.0$
- Silicon Vertex Tracker $|\eta| < 1$

Trigger Detectors

- Beam-Beam Counters $3.4 < |\eta| < 5$
- Zero-Degree Calorimeter $|\eta| \sim 6$

+ E-M Calorimeters - installation in stages to be completed before 2006

- Barrel EMC $|\eta| < 1$
- Endcap EMC $1.0 < \eta < 2.0$
- Forward Pion Detector $3.3 < |\eta| < 4.1$



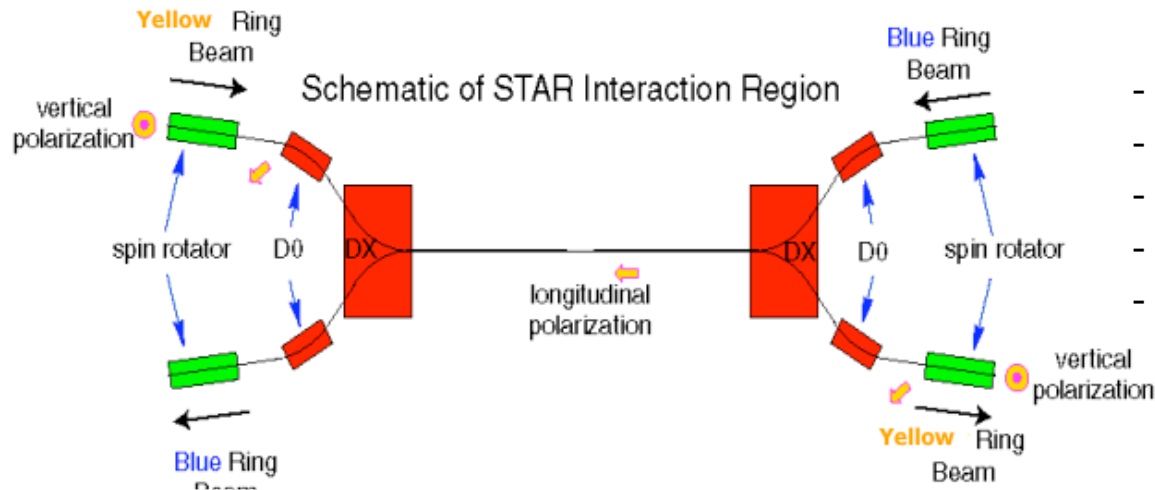
where pseudorapidity $\eta = -\ln \tan \theta/2$

STAR continues to add EM calorimetry to detect high-energy γ , e^\pm , π^0 (wide η region)

TPC+EMC for jet reconstruction

BBC + scaler board system for relative luminosity and polarization monitoring

BBC - Local Polarimeter at STAR



- Stable spin direction at RHIC is vertical
- Spin Rotater brings to almost radial
- D0/DX magnet causes spin precession
- Longitudinal at IR
- DX/D0/Spin Rotater put back to vertical

Measured asymmetry_i ~ A_N P_i

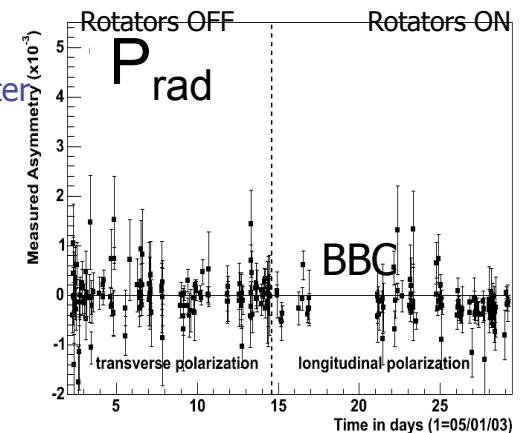
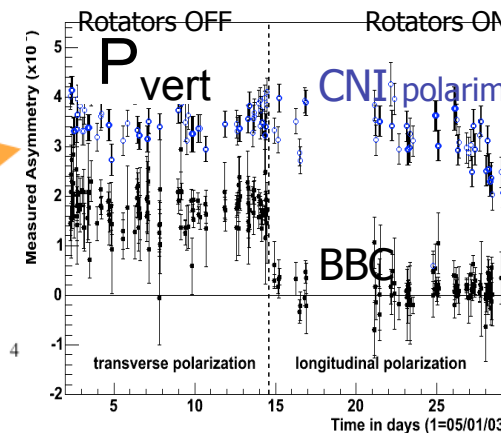
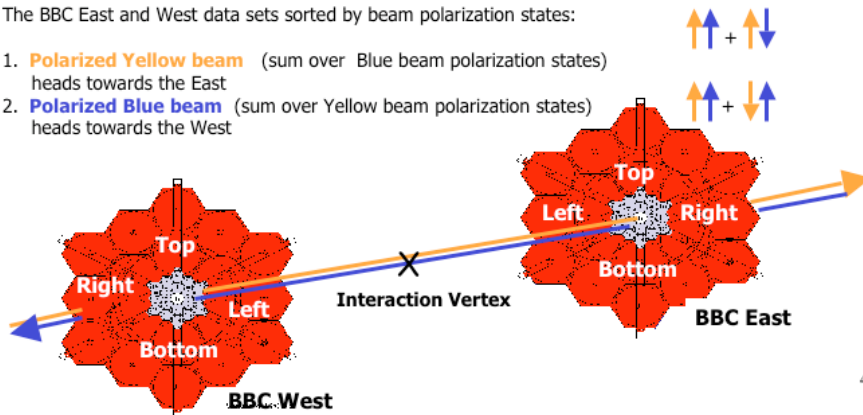
Left-Right asym - sensitive to vertical polarization

Top-Bottom asym - sensitive to radial polarization

Rotators	OFF	ON
CNI polarimeter	non-zero	non-zero
BBC Left-Right (vertical)	NON_ZERO	ZERO
BBC Top-Bottom (radial)	zero	zero

The BBC East and West data sets sorted by beam polarization states:

1. **Polarized Yellow beam** (sum over Blue beam polarization states) heads towards the East
2. **Polarized Blue beam** (sum over Yellow beam polarization states) heads towards the West

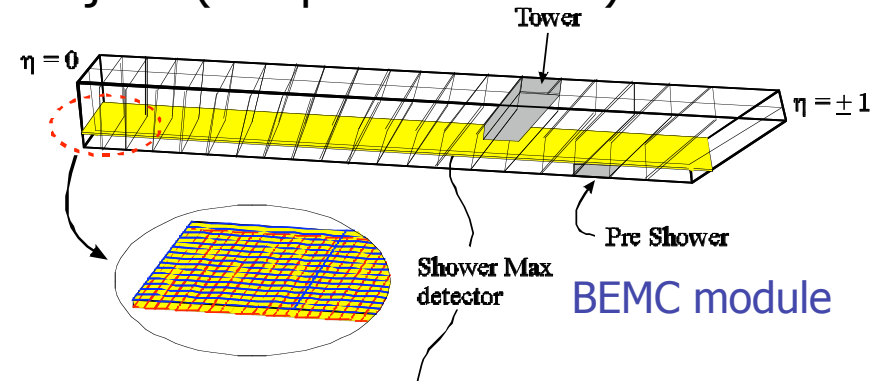


Long. polarization at STAR (2003 P_{vert} and P_{rad} < 3%) - first step to A_{LL} measurement

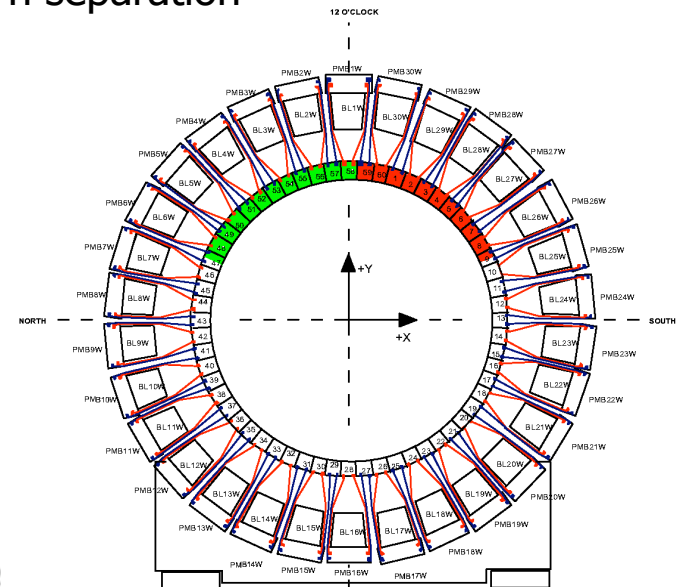
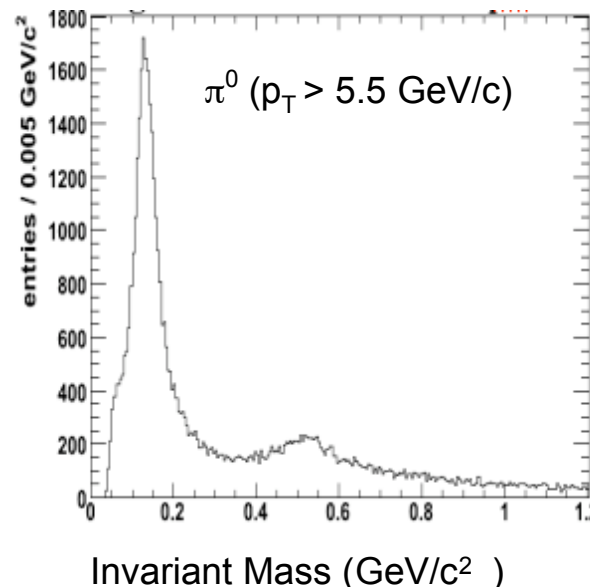
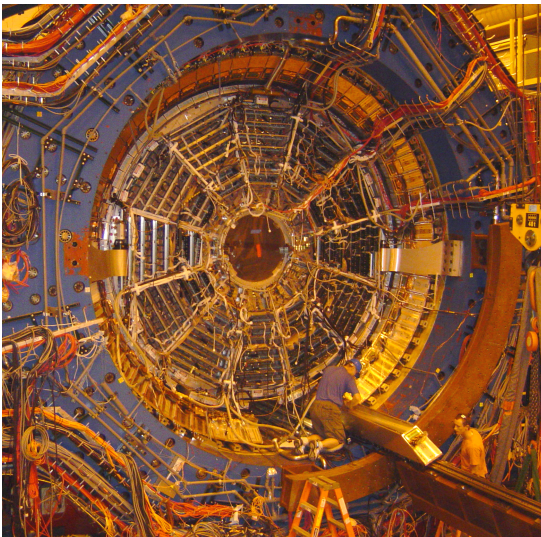
STAR Electromagnetic Calorimeter at mid-rapidity

Barrel EMC (BEMC) - a lead-scintillator sampling calorimeter, used to detect and trigger on high p_T photons and jets (completed in 2005)

- Coverage $|\eta| < 1$ and $\Delta\phi = 2\pi$
[TPC coverage $|\eta| < 1.6$ and $\Delta\phi = 2\pi$]
- 120 modules, total 4800 towers
($\Delta\eta \times \Delta\phi$)_{tower} = 0.05 X 0.05
- Depth $\sim 21 X_0$
- Energy resolution $dE/E \sim 16\%/\sqrt{E}$



Shower Maximum Detector (SMD) – located at $\sim 5 X_0$ in BEMC, a detector with high spatial resolution ($\Delta\eta \times \Delta\phi$)_{tower} = 0.007 X 0.007, used for γ/π^0 and e/h separation



STAR Electromagnetic Calorimeters in forward region

■ Endcap EMC (EEMC)

Lead-scintillator calorimeter ($\sim 24 X_0$)

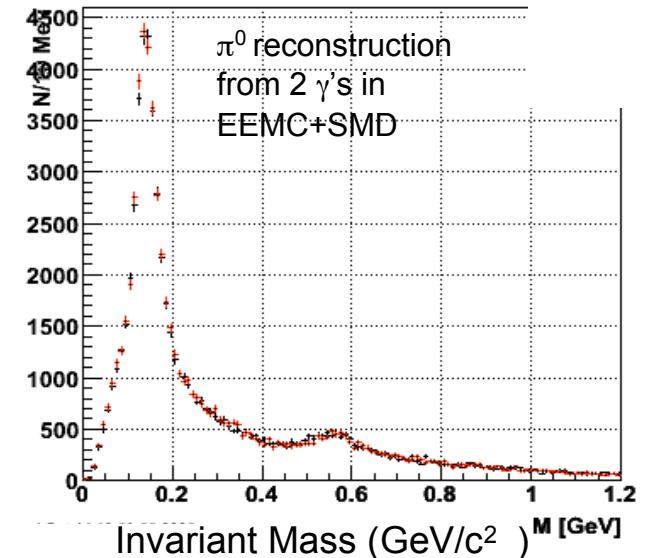
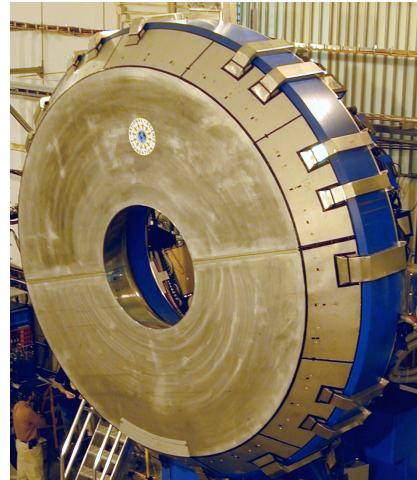
□ $1 < \eta < 2$ and $\Delta\phi = 2\pi$

□ 720 towers with: $\Delta\phi = 0.1$

$\Delta\eta = 0.06$ at $\eta = 1.1$ to $\Delta\eta = 0.1$ at $\eta = 2$

Shower max. detector (SMD): scintillator strip layers (π^0/γ discrimination)

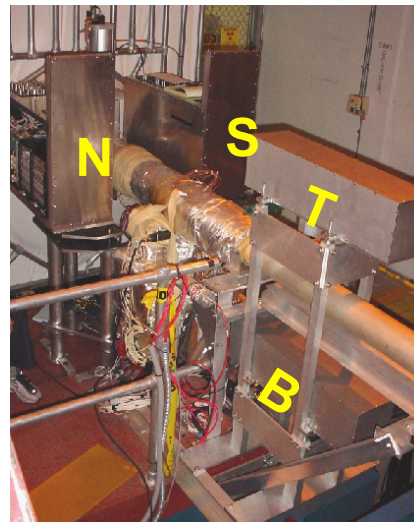
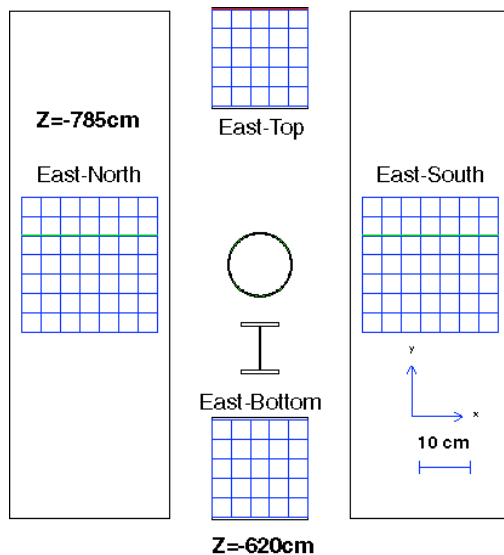
Completed in 2005



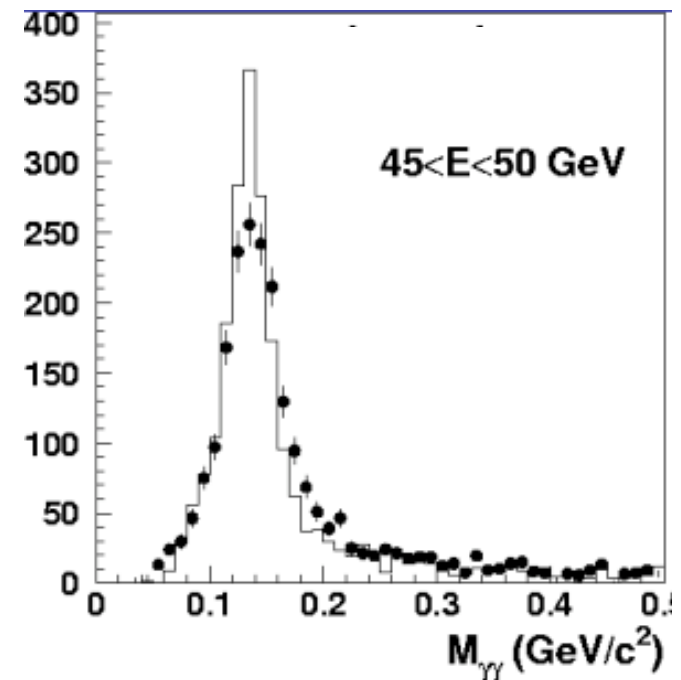
■ Forward Pion Detector (FPD)

□ Lead-glass calorimeter $3.3 < |\eta| < 4.0$

□ 4 modules (left/right/top/bottom)
expanded for 2006-2007



□ Shower max. detector (SMD):
scintillator strip layers (π^0/γ
discrimination) in left/right modules



Jet reconstruction at STAR

- via TPC p_T for charged hadrons+EMC E_T for e-m showers

1) **Jets reconstruction** - midpoint cone algorithm (Tevatron II)

seed energy = 0.5 GeV, cone angle $R = 0.4$ in η - ϕ

splitting/merging fraction $f=0.5$

2) **Trigger** used in this analysis - **High Tower**:

$E_T > 2.4$ GeV deposited in one tower ($\Delta\eta \times \Delta\phi$) = (0.05 x 0.05)

+ additional requirement of BBC coincidence.

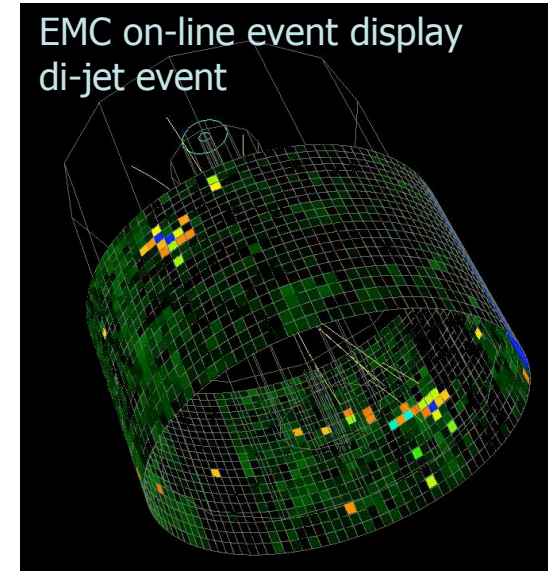
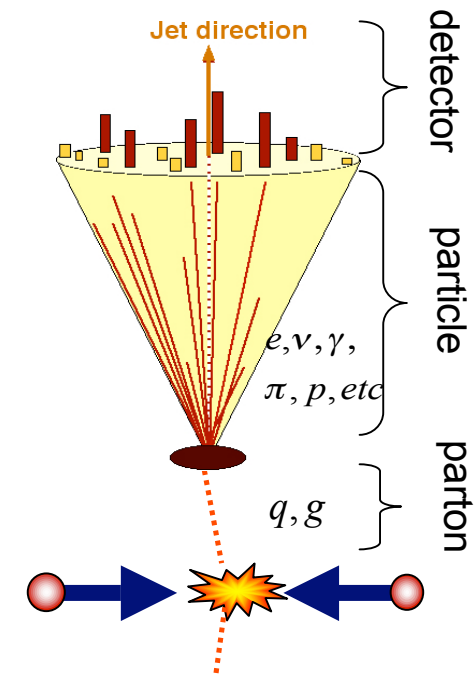
3) **Cuts** on:

- charged tracks $|\eta| < 1.6$ and $p_T > 0.1$ GeV/c
- **jets**: $p_T \text{ jet} > 5$ GeV/c , $0.2 < \text{jet } \eta \text{ (det)} < 0.8$
- background: $E_{\text{jet}}(\text{neutral})/E_{\text{jet}}(\text{total}) < 0.9$ (2004) and < 0.8 (2003)
- $|z\text{-vertex}| < 75\text{cm}$ (2003) and $< 60\text{cm}$ (2004)
- tower $E_T > 3.5$ GeV software threshold (only 2004 cross section)

4) **Data set**: 0.4 pb^{-1} (2003 and 2004) recorded luminosity
 $\langle P_b \rangle = 0.3$ (2003) and $\langle P_b \rangle = 0.4$ (2004)

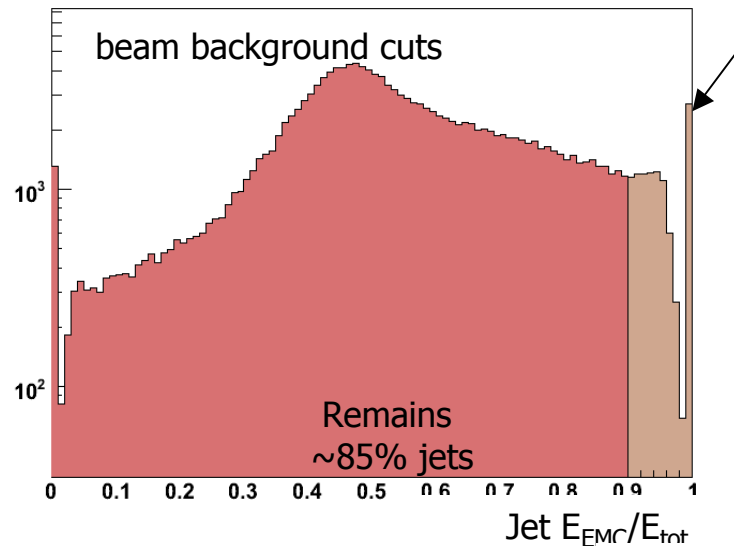
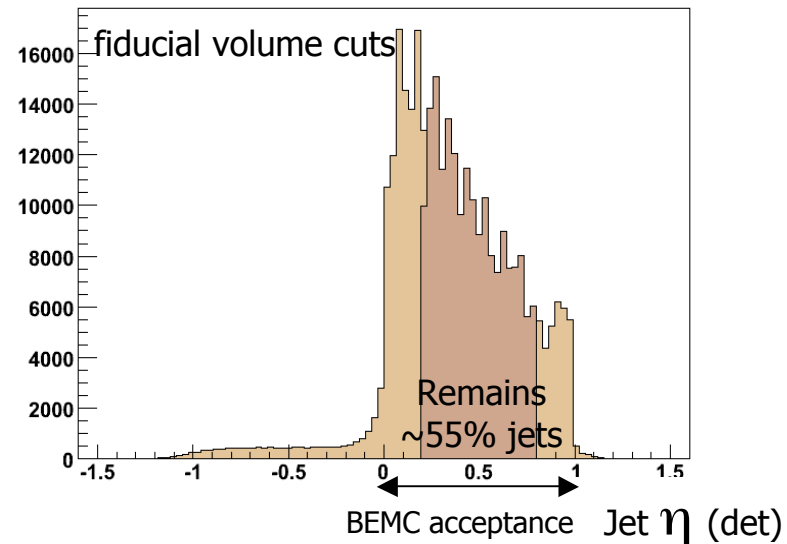
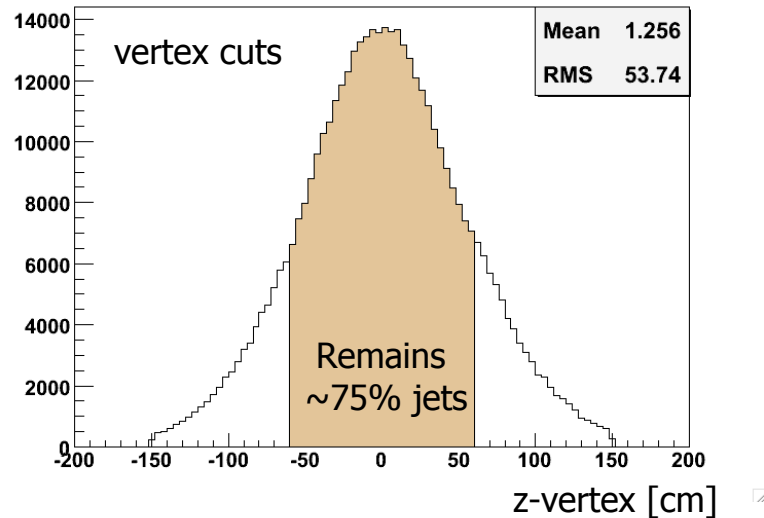
5) **Final statistics** (after cuts) for:

- cross section : 55k jets (2004)
- A_{LL} asymmetry: 125k (2003) and 162k (2004) jets



Effect of cuts on jet statistics (e.g. 2004)

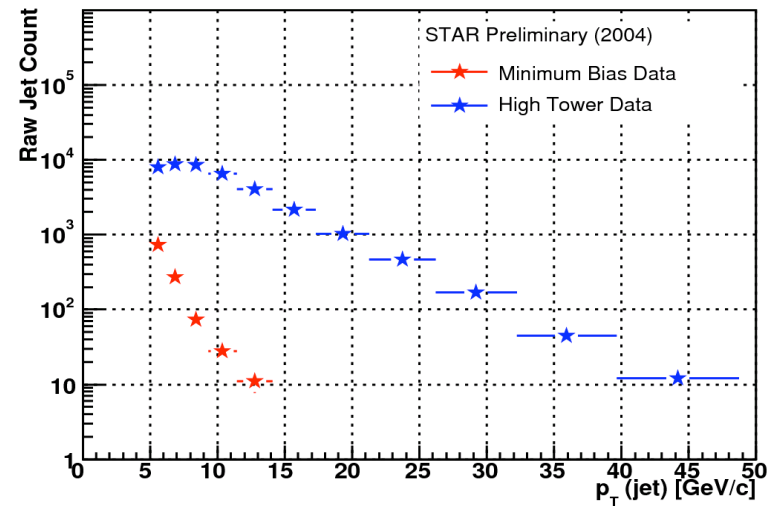
Initial sample = 1.4 M HighTower trigger events (0.4 M jets reconstructed)



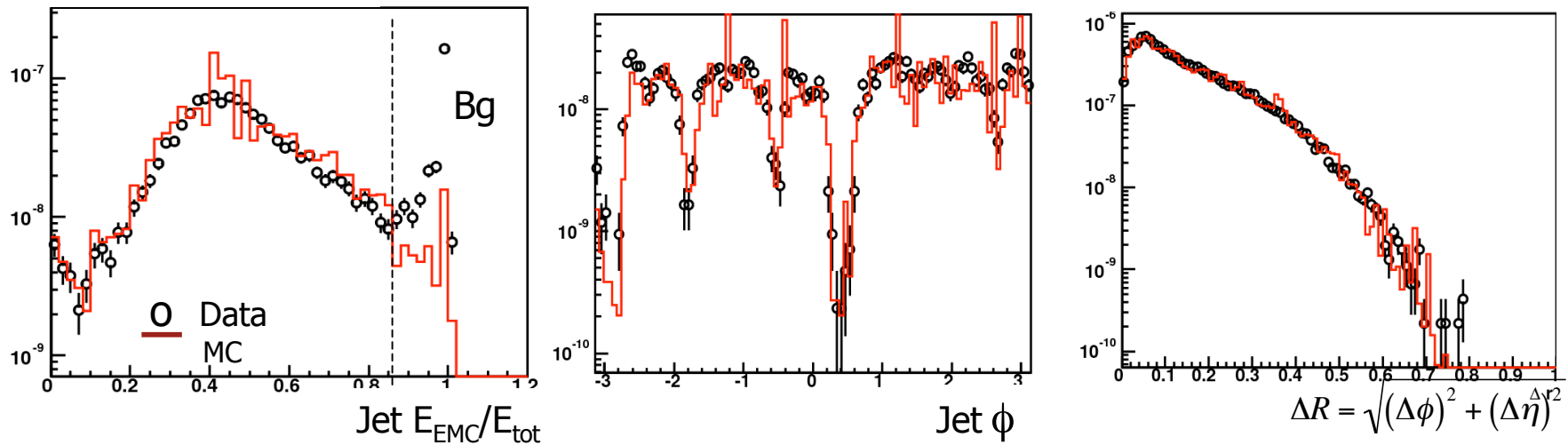
Fraction of fake (streaky) jets with only neutral energy strongly correlate with beam background levels monitored by the BBC. Shielding @STAR installed during 2005 summer shutdown.

Number of jets (HighTower events)
about ~35% jet survives these cuts
-160k final (2004) statistics for A_{LL}
analysis

- Raw Jet Count (High Tower and Minimum Bias data) - after all cuts



- Data and Monte Carlo comparison (HighTower trigger, $p_T(\text{jet}) > 10 \text{ GeV}$)



Monte Carlo (Pythia+Geant for STAR) well describes the data for $p_T(\text{jet}) > 10 \text{ GeV}$

Cross section for inclusive jet production

$$\frac{1}{d\Omega} \frac{d\sigma}{dp_T} = \frac{1}{2\pi \cdot 0.6} \cdot \frac{1}{\Delta p_T} \cdot \frac{1}{\int L \cdot dt} \cdot \frac{1}{c(p_T)} \cdot \frac{dN}{dp_T}$$

$$\frac{1}{\int L \cdot dt} = \frac{\sigma_{BBC} \cdot \epsilon_{vert}^{MB}}{N_{MB-events}^{accepted}}$$

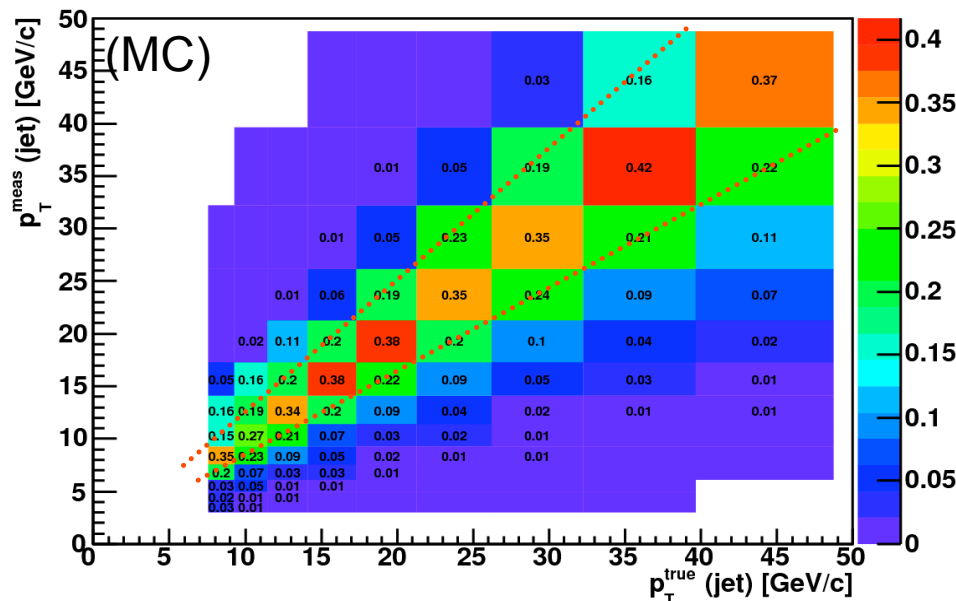
$$\frac{1}{N_{MB-events}^{accepted}} (MB) \rightarrow \frac{1}{N_{MB-events}^{accepted} \cdot \langle p_{MB}^{trig} \rangle} (HighTower)$$

$$resolution: \frac{p_T^{true} - p_T^{meas}}{p_T^{true}} \sim 25\% \pm 5\%$$

$$purity: \frac{N_{measured}}{N_{generated}}$$

From simulations. Consistent result obtained from di-jet evts

- Bins of width 1-sigma (**resolution**)
→ “**purity**” of ~35% over range on the diagonal.
- Motivates application of bin-by-bin correction factors:



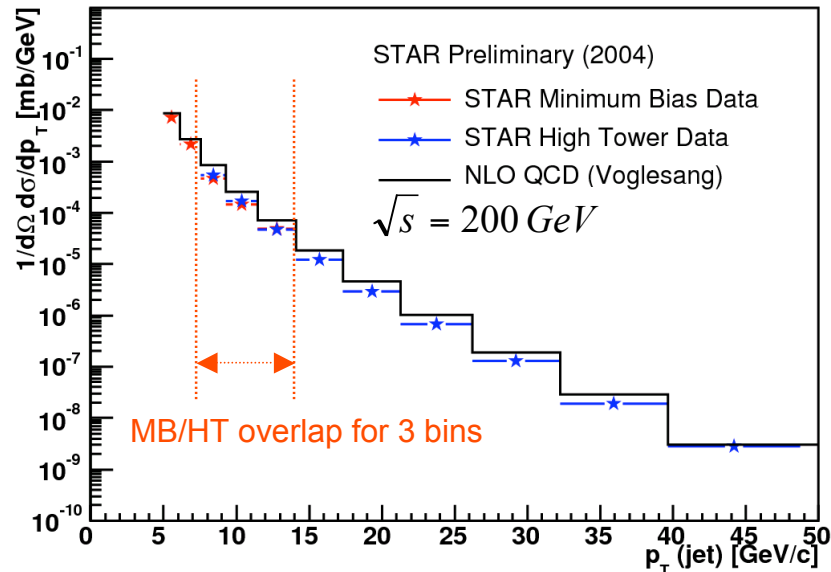
$$c(p_T) = \frac{M_{geant}(p_T^{geant} \leftarrow \text{“measured”})}{N_{pythia}(p_T^{pythia} \leftarrow \text{“true”})}$$

$$c \sim 1 \quad \text{at } p_T \sim 5-10 \text{ GeV/c} \quad (MB)$$

$$c \sim 1 \quad \text{at } p_T \sim 35-50 \text{ GeV/c} \quad (HighTower)$$

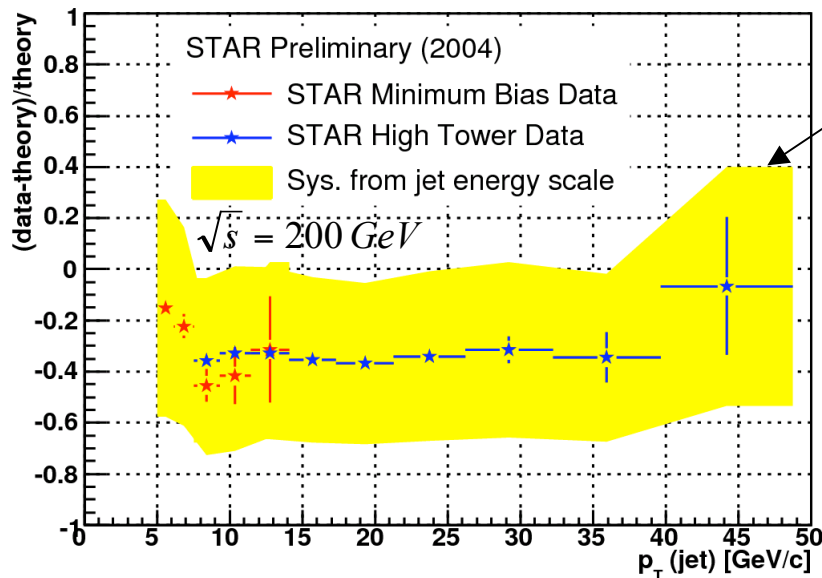
$$c \sim 0.01 \quad \text{at } p_T \sim 5 \text{ GeV/c}$$

Preliminary results for the cross section in inclusive jet production in p+p at $\sqrt{s}=200$ GeV vs NLO Calculation



- MB and HT data agree in overlap region

- NLO QCD - Fortran code from:
hep-ph/0404057 (Jager et al.)
 $R_{\text{cone}}=0.4$, CTEQ 6.1 $\mu_F = \mu_R = p_T$



- 50% systematic uncertainty from energy-scale (dominant) shown.
- Other sources of systematic uncertainties (smaller, not shown): normalization, BBC trigger efficiency, background contribution, ...
- Agreement (within systematics) over 7 orders of magnitude

Double Longitudinal Spin Asymmetry Measurements

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \times \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$

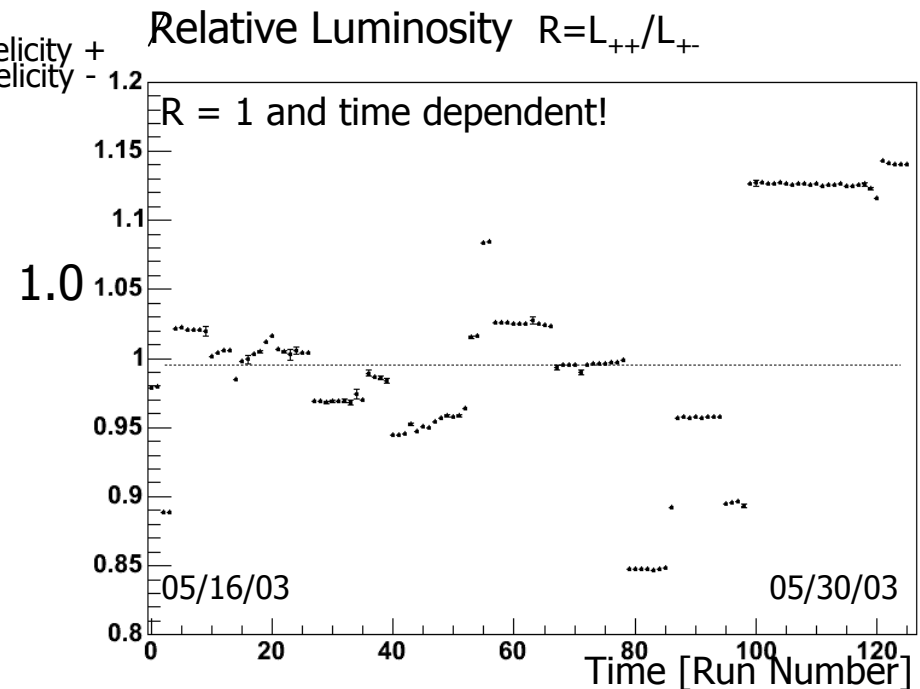
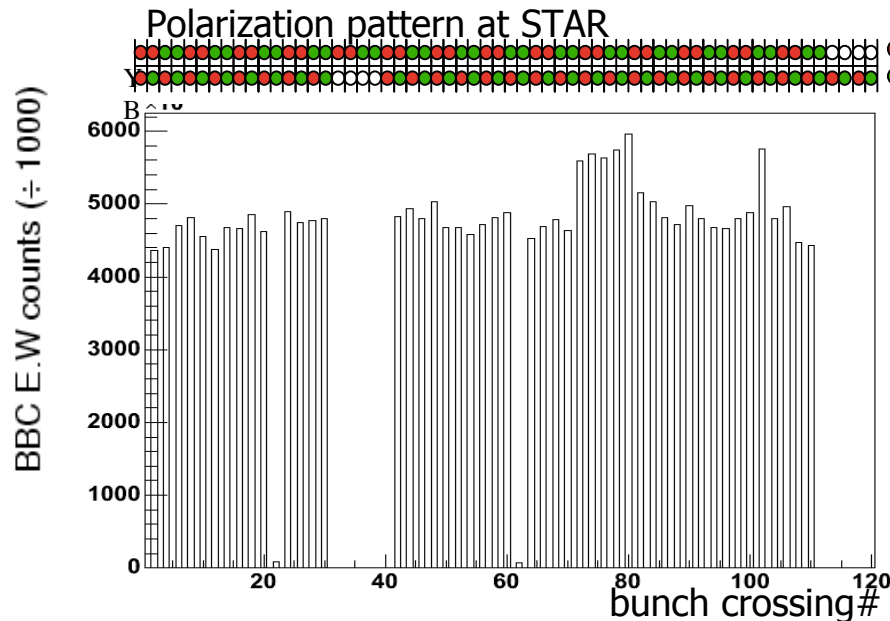
Statistical significance: $P_1^2 P_2^2 \cdot \int \mathcal{L} dt$

Require concurrent measurements:

- magnitude of beam polarization, $P_{1(2)}$
 - direction of polarization vector at interaction point
 - relative luminosity of bunch crossings with different spin directions: $R = \frac{L_{++}}{L_{+-}}$
 - spin dependent yields of process of interest N_{ij}
- RHIC polarimeters
- } BBC + scalers
- } STAR experiment

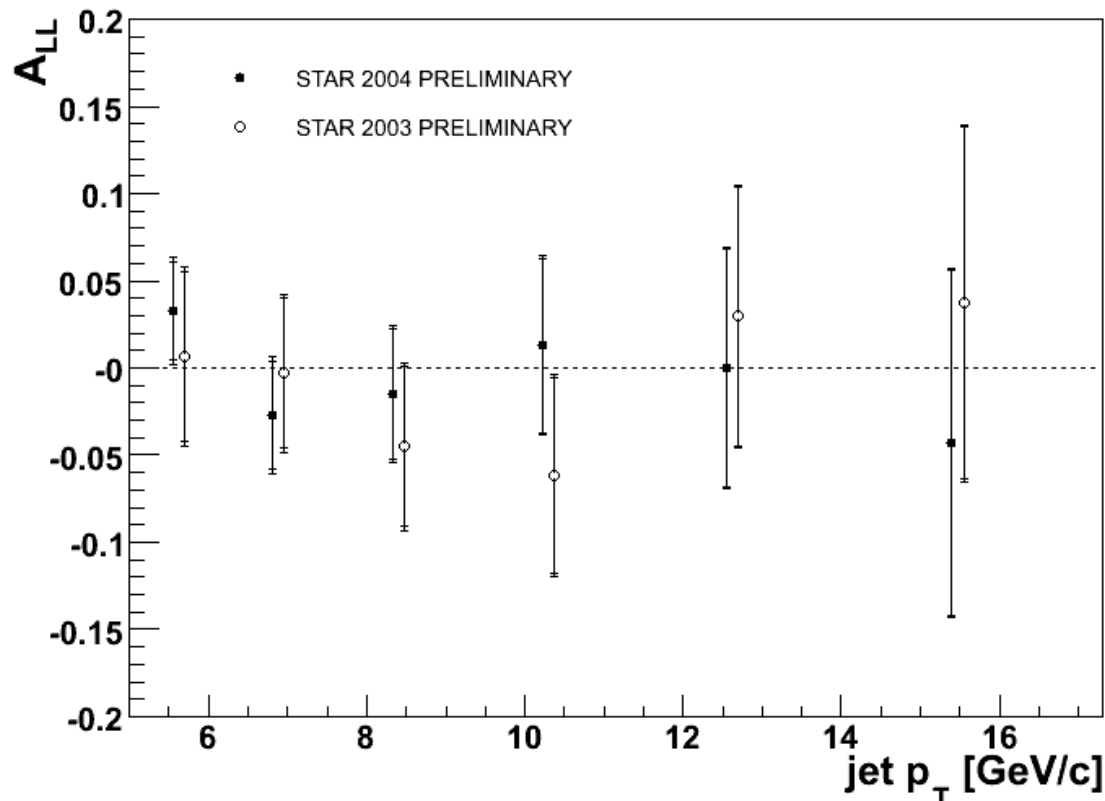
Relative Luminosity Measurement from Beam Beam Counters

- Precision of relative luminosity monitoring critical: for $A_{LL} \sim 1\%$ $\delta A_{LL}/A_{LL} \sim 5\%$ if $\delta R/R \sim 10^{-3}$
- Luminosity \sim BBC coincidence rate (large cross section of $\sim 27\text{mb}$) counted every 107ns
- RHIC stores up to 120 bunches per ring - different bunches injected with different spin orientation
- collision luminosity can vary with spin combination



Relative luminosities uncertainties: $\delta R_{\text{stat}} \sim 10^{-4} - 10^{-3}$ and $\delta R_{\text{syst}} < 10^{-3}$

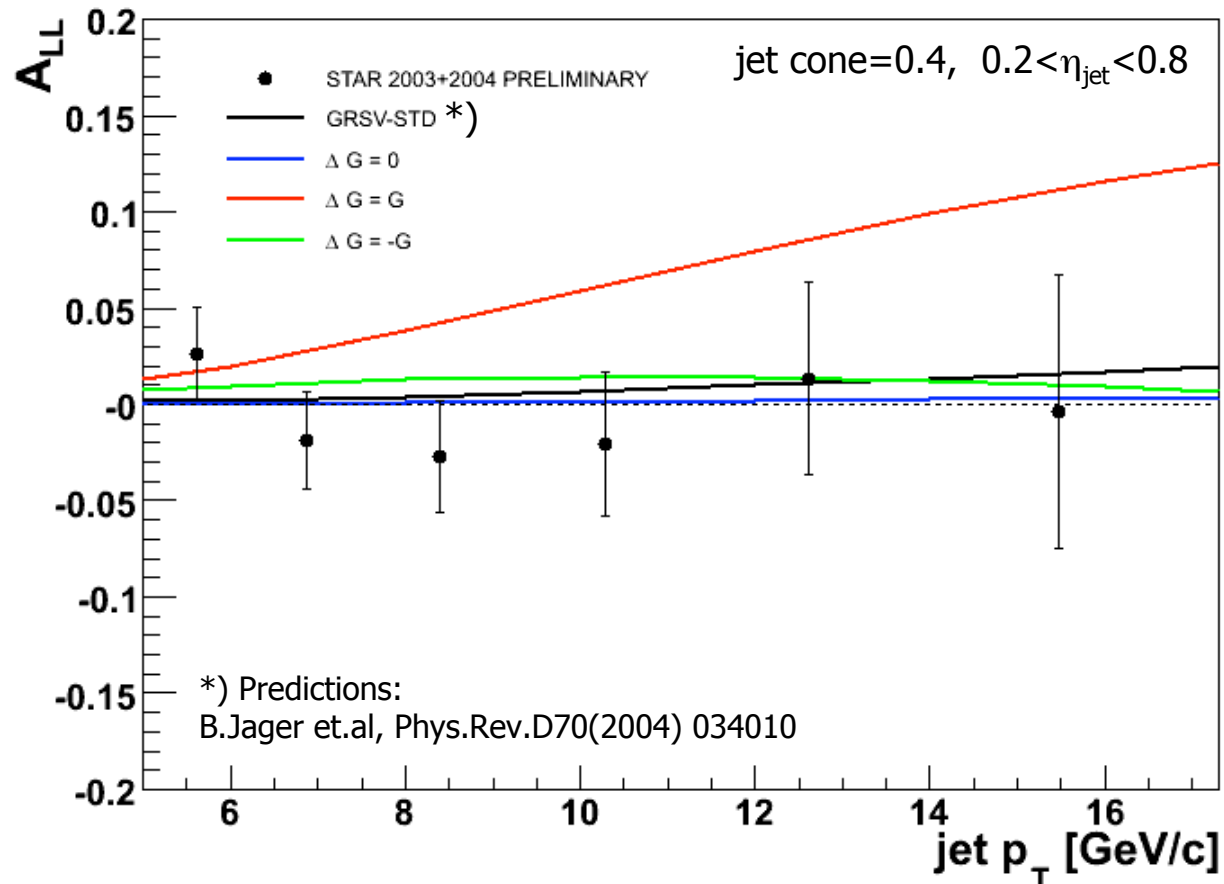
Double spin asymmetry A_{LL} (preliminary) results in inclusive jet production in p+p collisions at $\sqrt{s}=200\text{GeV}$



- Consistent results from 2003 and 2004 analyses
- Results limited by statistical precision
- Total systematic uncertainty ~ 0.01 (STAR) + beam polarization (RHIC)

Sources of systematic uncertainties: background contribution, trigger bias, relative luminosity, residual (non-longitudinal) asymmetries, bunch to bunch systematic variations (random pattern analysis) + beam polarization

Double spin asymmetry A_{LL} (preliminary) results in inclusive jet production in p+p collisions at $\sqrt{s}=200\text{GeV}$

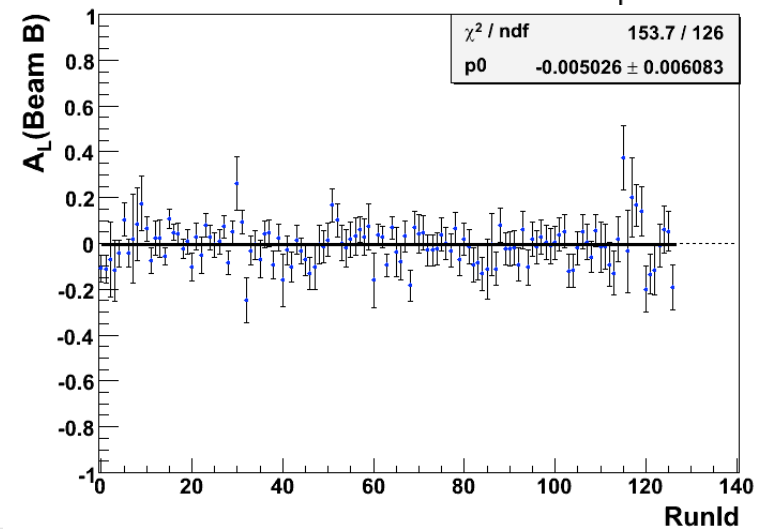
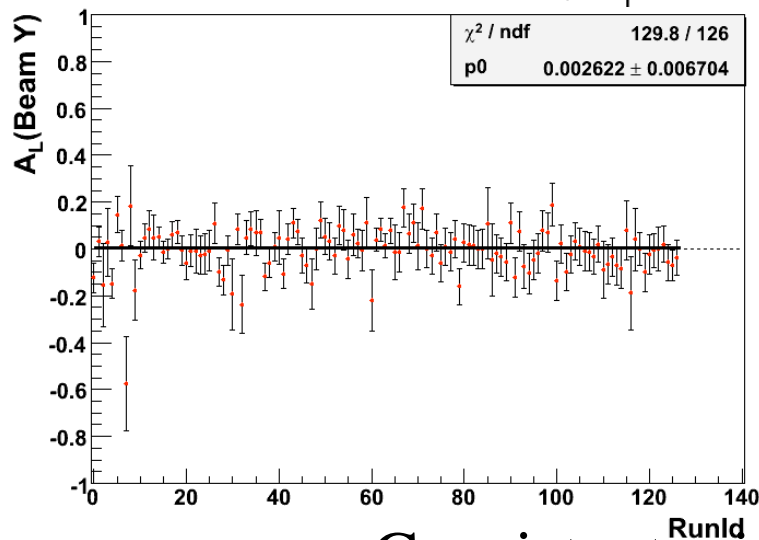
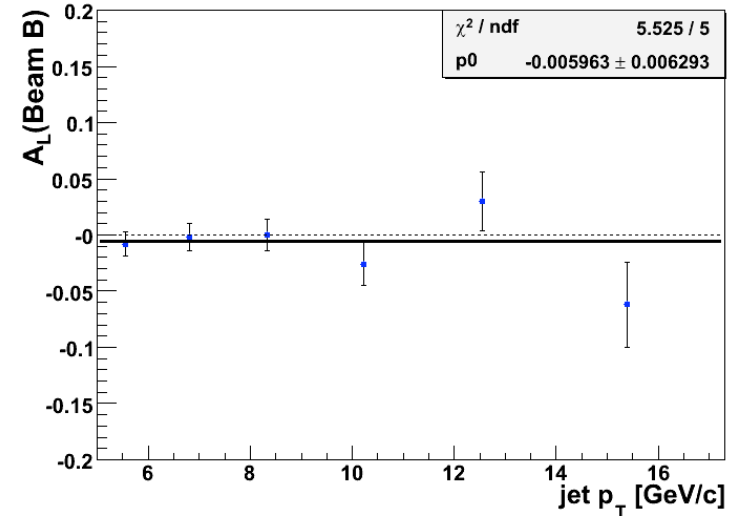
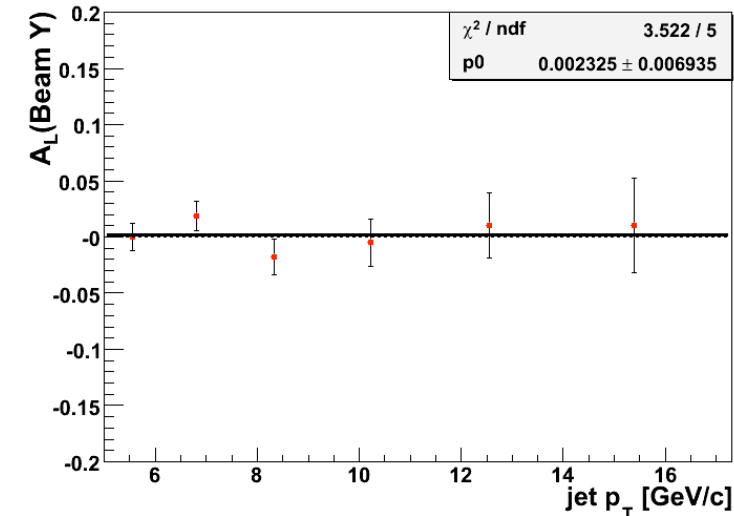


Results limited by statistical precision

Total systematic uncertainty ~ 0.01 (STAR) + beam pol. (RHIC)

GRSV-max scenario strongly disfavored

Cross checks - e.g. (2004) parity violating asymmetries

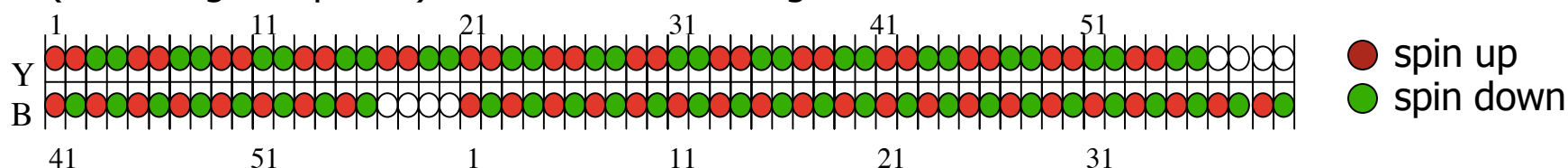


Consistent with zero - as expected

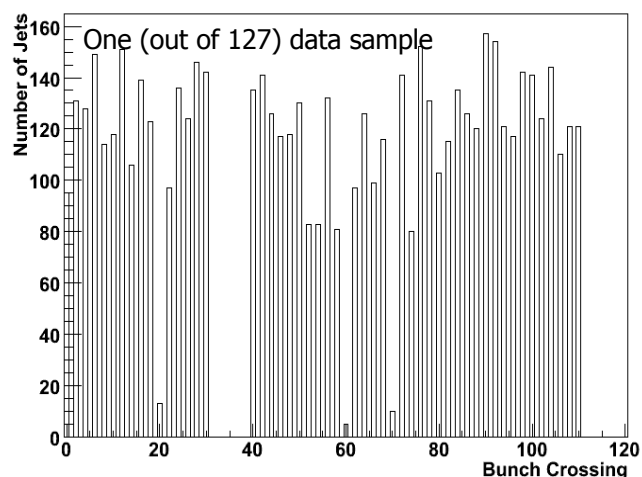
All other asymmetries were found consistent with zero

Systematic Study for A_{LL} - Random Fill Pattern Analysis

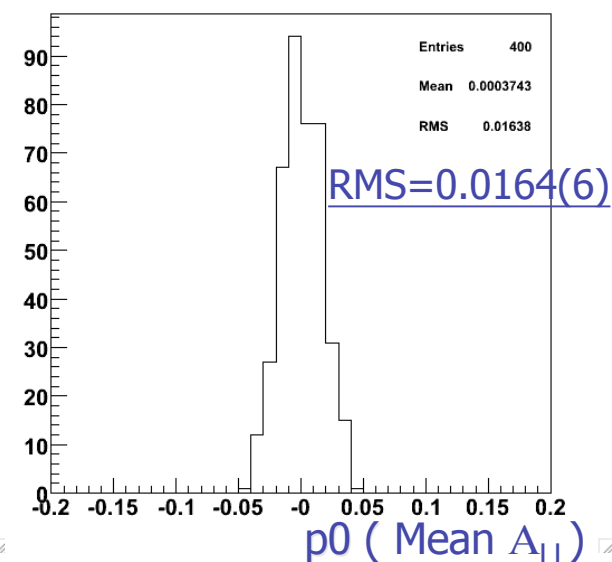
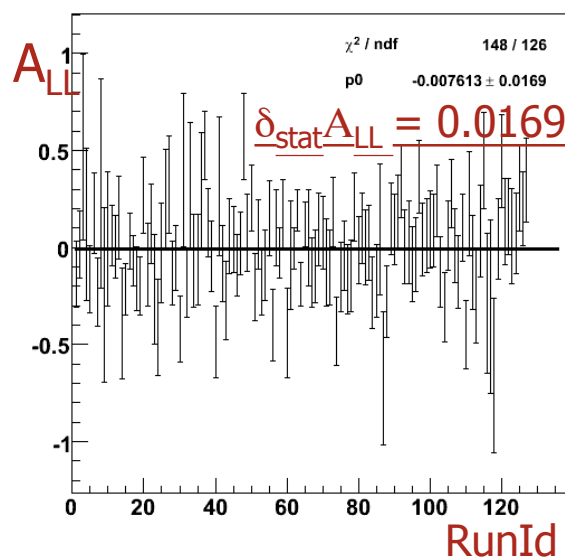
- Method: take **true fill pattern** (56 bunches in 2004) and mix assignment of spin up and down bunches (red and green points) to the bunch crossing number



Input



- Result for: **one random fill pattern** and **400 random fill patterns**



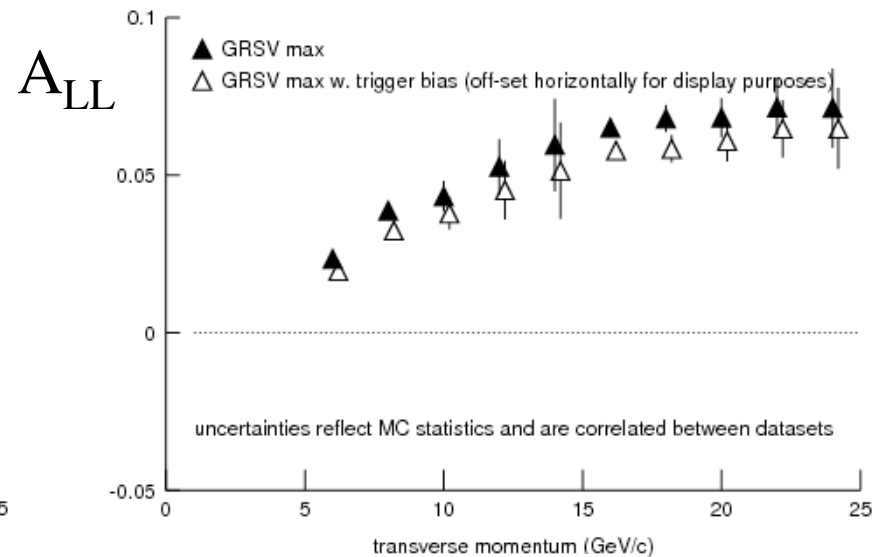
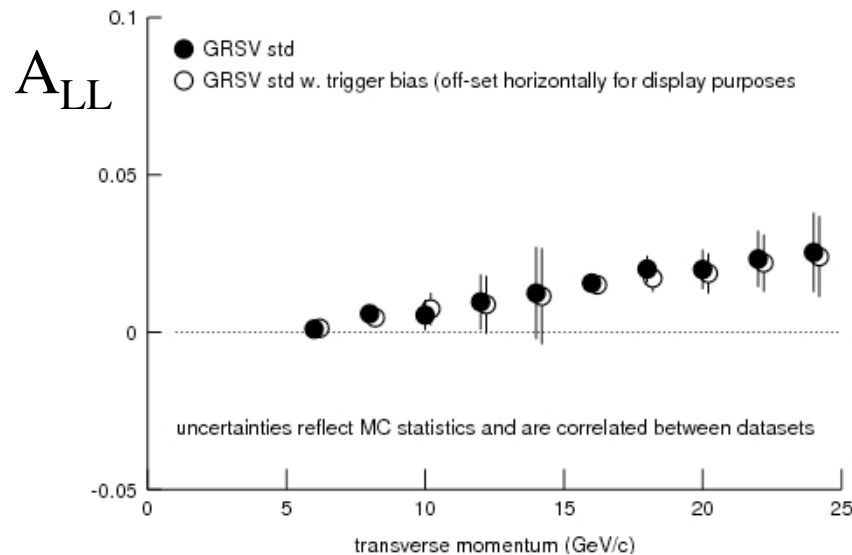
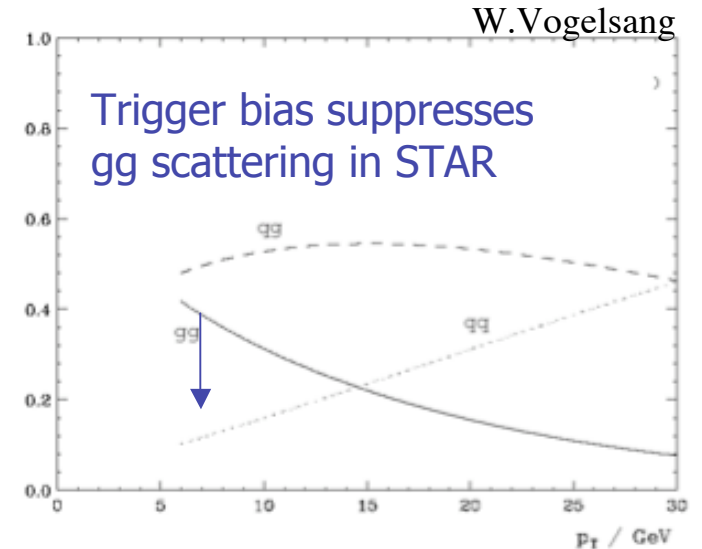
The RMS is consistent with A_{LL} statistical uncertainties indicating that bunch to bunch and fill to fill systematic uncertainties are negligible

A_{LL} systematics - a closer look

- Trigger bias

High Tower trigger ($E_T > 2.4$ GeV deposited in one tower) selects on e-m energy deposits and may thus distort the partonic subprocess contributions in inclusive jet production.

Possible size of this effect was estimated from MonteCarlo (Pythia+GEANT) simulations of the trigger response, and from various polarized parton distribution functions such as GRSV-std and -max.



$$|A_{LL}(\text{with bias}) - A_{LL}(\text{no bias})| < 0.007$$

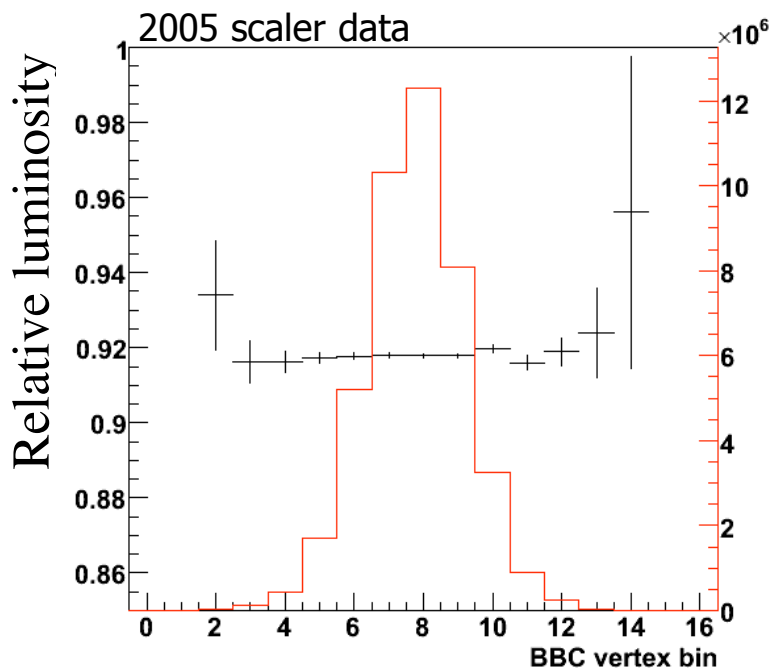
Status of Run5 data analysis

Improvements for Run5 (Spring 2005)

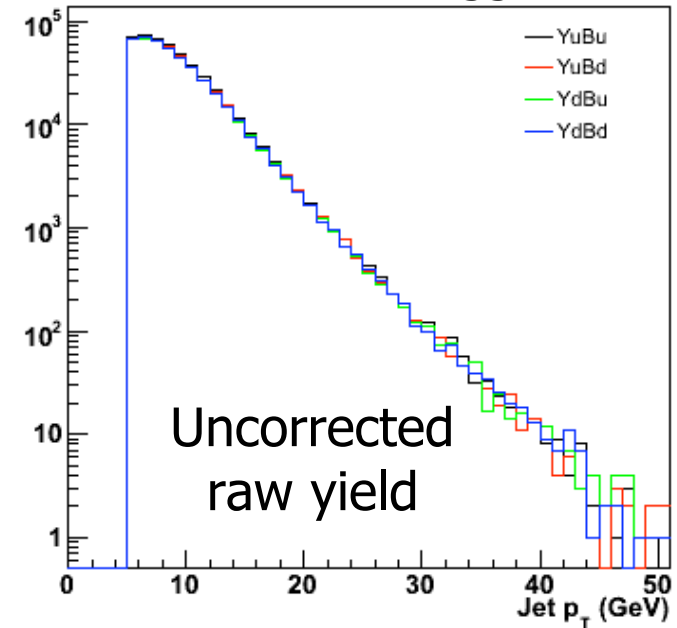
- $P_b \sim 45\%$ ($\sim 40\%$ in Run4) $L = 3/\text{pb}$ ($0.3/\text{pb}$ in Run4)
 $\text{FoM}(\text{Run5})/\text{FoM}(\text{Run4}) = 16$
- Acceptance: 3/4 BEMC complete ($1/2$ in Run4)
- BEMC Jet-Patch ($\Delta\eta \times \Delta\phi = 1 \times 1$) trigger data collected in addition to High-Tower trigger data.

Jet sample:

- HT trigger $\sim 0.7\text{M}$ (0.16M in Run4)
- JP trigger $\sim 2.2\text{M}$ (test in Run4)

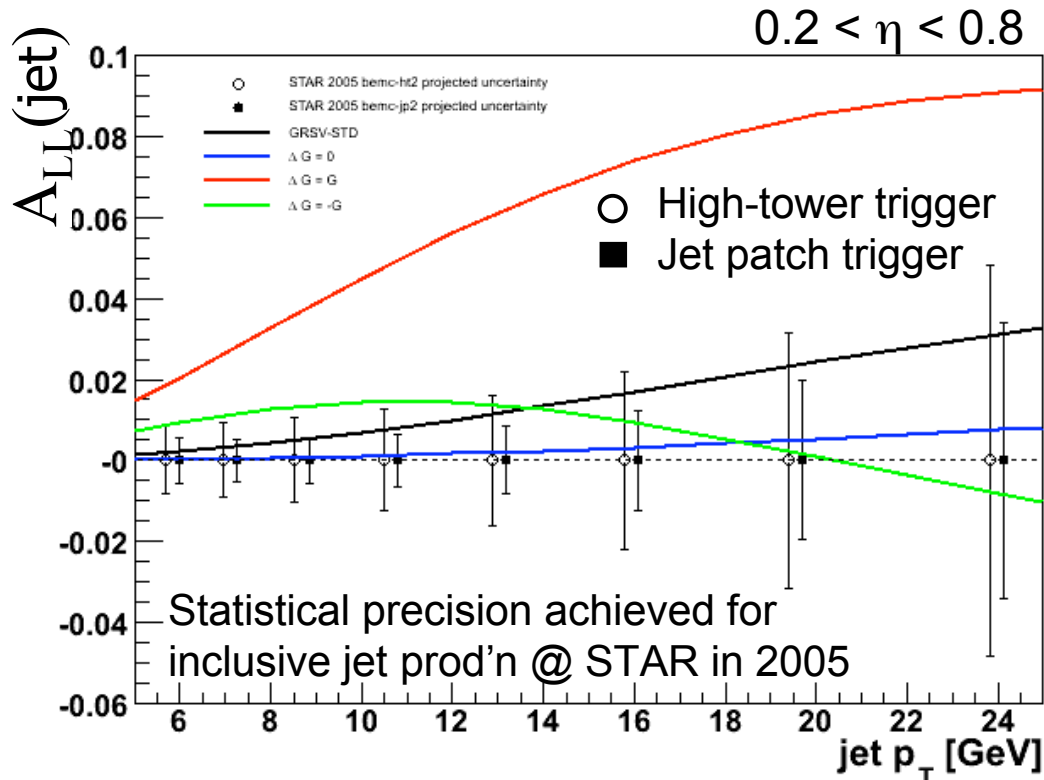


BEMC Jet-Patch trigger



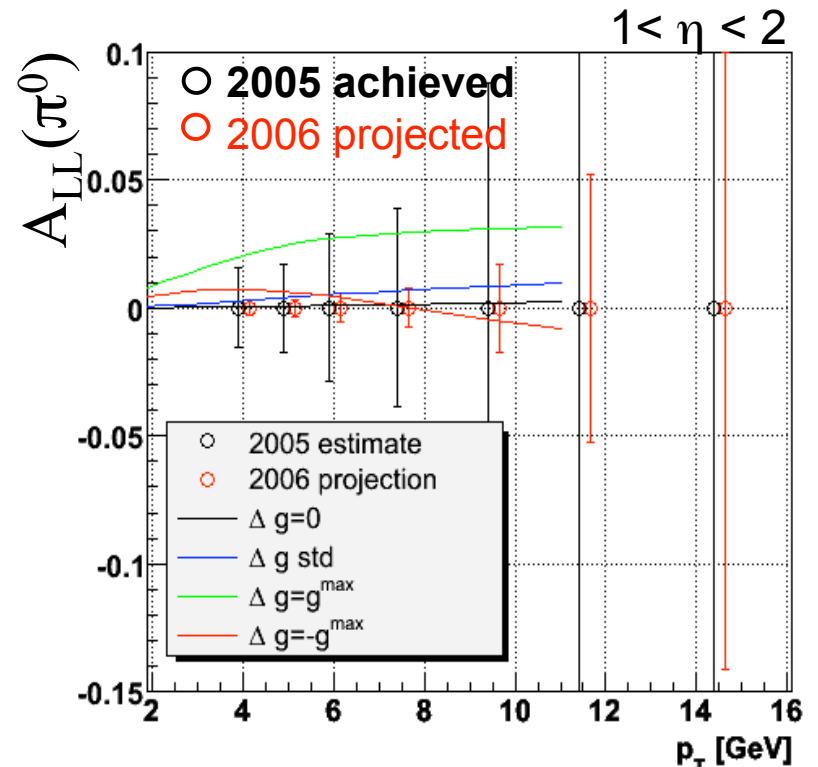
- The analysis of the more precise Run5 data is well under way.
- We are studying systematic effects, such as spin dependent backgrounds to correspondingly refined levels of accuracy.
- For Run5 the relative luminosities are resolved in vertex-z (additional scaler boards)

Prospects for Run5 - first long pp run



Two complementary jet triggers permit assessment of trigger bias due to q vs. g jet differences in shape, multiplicity, hardness in z.

Potential to *discriminate* between several of the expectations based on DIS parametrizations (not all of which are equally probable).



$A_{LL}(\pi^0)$ in 2005 - limited statistical precision. Theoretical predictions: A_{LL} values in forward region smaller than at midrapidity

Summary and Outlook (1)

We present preliminary results for the measurement of the cross section and the double spin asymmetry A_{LL} in inclusive jet production in polarized p+p collisions at $\sqrt{s}=200$ GeV

- The data was collected during 2 weeks in 2003 (first physics pp run at RHIC with longitudinally polarized beams) and 2 weeks in 2004 (commissioning run) with average beam polarizations of about 30% in 2003 and 40% in 2004.
- The cross section agrees within large systematic errors with NLO QCD calculations over the measured (large!) range $5 < p_T < 50$ GeV/c.
- The asymmetry A_{LL} is consistent with evaluations based on DIS over the measured kinematic range of jet $5 < p_T < 17$ GeV/c.
- The results for A_{LL} are limited by statistical uncertainties of about 0.015 and currently do not distinguish between the different scenarios for gluon polarization in the proton allowed by polarized DIS data.
- GRSV-max (scenario which assumes $\Delta G(x)=G(x)$ at $Q^2=0.6$ GeV²/c² input scale) is strongly disfavored by STAR data.

Summary and Outlook (2)

Prospects for Run5 (finished in June 2005)

In run-5 STAR collected ~ 10 times more statistics (the first long pp run) with higher beam polarization (better source) than in 2003 and 2004.

STAR will be able to distinguish between the different scenarios for gluon polarization in the proton from A_{LL} measurement in (i) inclusive jet production at mid-rapidity (ii) inclusive π^0 production at mid-rapidity and forward region (STAR unique!)

....and beyond

Measurements with rare probes: A_{LL} in inclusive γ , γ +jet and di-jets correlations at $\sqrt{s}=200$ and 500 GeV.

Essential requirements on STAR detector capabilities:

- Fully operational BEMC and EEMC - Both are fully in place for 2006 and beyond
- Shielding around STAR IR (to reduce backgrounds) in place for 2006 and beyond

Continuous effort for luminosity (running time!) and beam polarization development needed!

How to analyze these data at STAR (various channels, NLO) to obtain the best information on both $G(x, Q^2)$ and integral $\Delta G(Q^2) = \int_0^1 \Delta G(x, Q^2) dx$

0

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